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Continuously operating compact ^{3}He-based neutron spin filter

G.L. Jones[a],*, J. Baker[a], W.C. Chen[b,d], B. Collett[a], J.A. Cowan[e], M.F. Dias[a], T.R. Gentile[b], C. Hoffmann[c], T. Koetzle[e], W.T. Lee[c], K. Littrell[e], M. Miller[e], A. Schultz[e], W.M. Snow[d], X. Tong[d], H. Yan[d], A. Yue[a]

[a]*Department of Physics, Hamilton College, Clinton, NY 13323, USA*
[b]*National Institute of Standards and Technology, Gaithersburg, MD 20899, USA*
[c]*Spallation Neutron Source, Oak Ridge, TN 37831, USA*
[d]*Indiana University, Bloomington, IN 47408, USA*
[e]*Argonne National Laboratory, Argonne, IL 60439, USA*

Abstract

Polarized ^{3}He can be used as a spin filter to polarize a broad energy spectrum of neutrons. As a prototype for use on the single-crystal diffractometer (SCD) at the spallation neutron source (SNS), we have built a compact system to continuously polarize a ^{3}He spin filter by spin-exchange optical pumping. Polarizing in the neutron beam provides a constant neutron polarization and reduces the sensitivity to relaxation mechanisms. The capability to operate in the presence of non-optimal magnetic field homogeneity allowed us to employ a highly compact solenoid only 9.5 cm in diameter and 20 cm long. Using only 7 W of laser light we maintained 44% ^{3}He polarization in an 11 cm^3 cell, despite an overall cell relaxation time of $\approx$ 10 h. Results from a test on the SCD at IPNS are discussed.
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1. Introduction

The single-crystal diffractometer (SCD) [1] at the spallation neutron source (SNS) will have the capability to study magnetic materials with polarized neutrons. As a step toward developing a broadband ^{3}He spin filter for the SCD, a continuously operating polarizer was tested on the SCD at the intense pulsed neutron source (IPNS) [2].

The highly spin-dependent neutron capture cross section of polarized ^{3}He gas can be used to polarize a broad energy range of neutrons up to epithermal energies [3,4]. ^{3}He-based spin filters

*Corresponding author. Tel.: +1 315 859 4697;
fax: +1 315 859 4807.

E-mail address: gjones@hamilton.gov (G.L. Jones).

have a large angular acceptance and no effect on beam divergence, which make them ideal for neutron scattering experiments. Although the polarizing efficiency of a neutron spin filter is wavelength dependent, it can be determined solely from transmission measurements which are convenient at spallation sources. In this paper, we present a design for a simple, compact, polarizer, shielded from minor stray magnetic fields, that can provide a constant neutron polarization over long-time periods.

2. Neutron spin filters

The total cross section for neutrons on ^{3}He is almost entirely due to capture of neutrons whose spins are anti-aligned with the ^{3}He spins. A polarized sample of ^{3}He almost completely transmits aligned neutrons while strongly absorbing anti-aligned neutrons. The neutron polarization produced by a ^{3}He spin filter depends on its thickness. A thin polarizer has little attenuation for either state but provides a low neutron polarization. A thick polarizer has more overall attenuation, but one polarization state is very highly attenuated and therefore it provides a high neutron polarization. Since the ^{3}He capture cross section is directly proportional to wavelength, $\sigma(\lambda) \approx \sigma_0 \lambda$, where $\sigma_0 = 29,662$ b/nm, and λ is the neutron wavelength in nanometers [5]. This energy dependence makes a typical polarizer look thin to fast neutrons and thick to slow neutrons. The neutron transmission T_n and polarization P_n are given as functions of λ by

$$T_n(\lambda) = T_0(\lambda) \cosh(P_{He} n \sigma_0 \lambda l), \tag{1}$$

$$P_n(\lambda) = \tanh(P_{He} n \sigma_0 \lambda l) = \left(1 - \frac{T_0^2(\lambda)}{T_n^2(\lambda)}\right)^{1/2}, \tag{2}$$

where

$$T_0(\lambda) = T_E \exp[-n \sigma_0 \lambda l] \tag{3}$$

is the neutron transmission through unpolarized ^{3}He, T_E is the transmission of the empty ^{3}He cell, P_{He} is the ^{3}He polarization, l is the thickness of the ^{3}He cell, and n is the number density of the ^{3}He. We assume that T_E is wavelength independent as

expected from the negligible neutron absorption in the glass. This was roughly confirmed in an auxiliary measurement on a piece of GE180 glass. In addition to showing the functional dependence of P_n on neutron energy, Eq. (2) shows that P_n can be determined solely from relative transmission measurements at each wavelength [6].

3. Apparatus

The compact polarizer is shown schematically in Fig. 1. The spin filter cell is continuously polarized by spin-exchange optical pumping [7,8] while in the neutron beam. The ^{3}He is contained in a sealed 1.7 cm diameter, 5 cm long blown GE180 [9] glass cell (named Oscar) filled with 2.6 bar of ^{3}He, 66 mbar of nitrogen, and ~ 0.05 g Rb. To increase the Rb vapor pressure in the cell, it is heated in an oven machined from a tube of high-temperature plastic [10] with an inner diameter of 4.75 cm. The central 10 cm length of the tube is closed off by double pane windows made from 1 mm thick fused silica glass. Hot air from a nearby heater enters at one end of the solenoid through a duct running longitudinally through the wall of the tube. The air escapes in holes around the windows.

The main solenoid is wound from 0.64 mm diameter (22 AWG) wire directly on the outside of the 8 cm diameter oven. At each end of the solenoid, a coil (18 turns) is wound in series with the main solenoid to compensate for end effects. An additional low current correction coil (50 turns) is wound on each end for fine tuning of the field. An 8.8 cm ID sleeve of 1.58 mm thick,
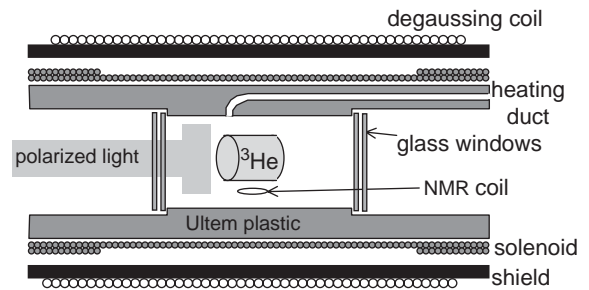

Fig. 1. Schematic diagram of the compact polarizer.

mu-metal [11] with relatively low permeability and high saturation surrounds the main coil. A spiral wrap of Teflon tubing centers the shield on the solenoid and allows cooling air to flow over the solenoid windings. Finally, a degaussing solenoid is wound directly on the shield [12]. To improve spin transport with such a small diameter solenoid, no end caps were used with the magnetic shield. The overall outer diameter is 9.5 cm, and the length is 20 cm.

For diagnostic purposes, free induction decay (FID) nuclear magnetic resonance (NMR) is performed using a small (1 cm × 3 cm) single coil taped to the glass cell. A computer controlled digital signal processor provides a RF pulse and readout of the free induction decay (FID) signal. The NMR signal size provides a relative monitor for the ^{3}He polarization, and the decay time of the FID signal (T_2^*) provides a measure of the magnetic field gradients for tuning the correction coils.

The solenoid and polarizing optics are mounted on the end of a 30 cm × 45 cm aluminum bread-board. Light from a 15 W fiber coupled diode laser array is expanded to a 3 cm diameter beam to fill the cell volume, and is split into two linearly polarized beams by a polarizing beam splitter cube. One beam is discarded, due to space constraints, while the other is circularly polarized by a $\lambda/4$ plate and reflected into the cell. The light is reflected into the cell by a mirror in the neutron beam. The mirror is made from 1 mm thick fused silica coated with a dielectric coating [13]. Using a dielectric coating rather than a metal coating preserves the circular polarization of the laser light. Light that passes through the cell is blocked by a piece of aluminum foil. Due to the optical density of the Rb vapor, there is little gain from the light reflected off the foil back through the cell.

The ^{3}He cell used for this test, had an atypically short lifetime of $T_1 = 20$ h, which limited the polarization to 51% in off-line tests at NIST. In the compact polarizer system, magnetic inhomogeneities contributed a comparable relaxation rate, [14] yielding an effective relaxation time of ≈ 10 h. Nevertheless, operating the cell at 184 °C yielded a pump up time constant of 3.5 h, which partially compensated for the short T_1. Although a longer

lifetime cell was available, we found that the polarization in the cell Oscar was superior due to a high X-factor in the longer lifetime cell [15,16].

4. Test run

The polarizer system was tested on the SCD at IPNS. As shown in Fig. 2, a 10 mm diameter neutron beam was polarized before scattering off a crystal into a two-dimensional detector. Several orders of Bragg peaks were identified by neutron wavelength (time of flight) and scattering angle.

To determine the neutron polarization and the ^{3}He polarization, the transmission was measured using two thin BF_3 monitor detectors. The variation of $T_0(\lambda)$ with wavelength, shown in Fig. 3, was determined from the ratio of measurements with the cell in and out of the beam. Eq. (3) allowed us to extract both $T_E = 0.88$ and the product $n\sigma_0 l = 10.7$ nm^{-1} from these data. The value of T_E corresponds to 6.5 mm of glass. The value of nl, which corresponds to 14.5 bar cm of ^{3}He gas, is 10% higher than the value determined from a measurement at a single neutron wavelength at NIST. This discrepancy is outside of the uncertainties of the two respective measurements and will be investigated. We note that using the NIST value would increase the measured ^{3}He polarization but would not alter the neutron polarization, which is extracted purely from relative transmission measurements. After polarizing the ^{3}He, $P_n(\lambda)$ was determined for each wavelength from Eq. (2). Fig. 4 shows $P_n(\lambda)$ and $T_n(\lambda)$. At a neutron wavelength of 0.31 nm, $P_n =$
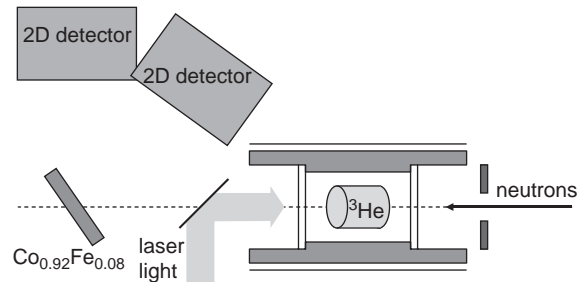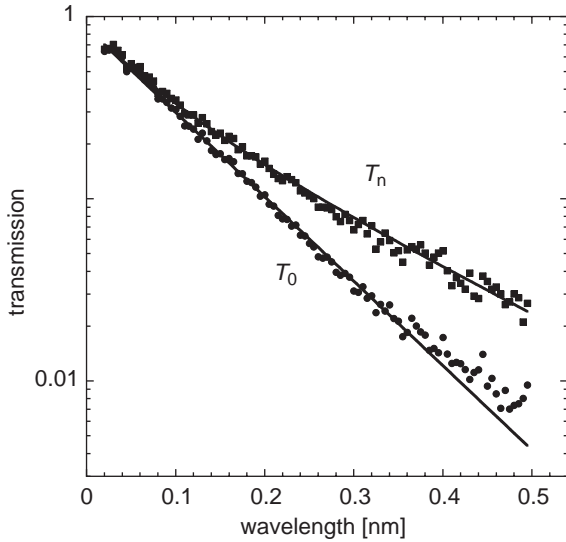
Fig. 2. Layout of SCD beamline.

Fig. 3. The absolute neutron transmission through the un-polarized (T_0) and polarized (T_n) ^{3}He cell vs. wavelength. The fit to T_0 (Eq. (3)) corresponds to 14.5 bar cm of ^{3}He gas and $T_E = 0.88$. The fit to T_n corresponds to $P_{He} = 44$.
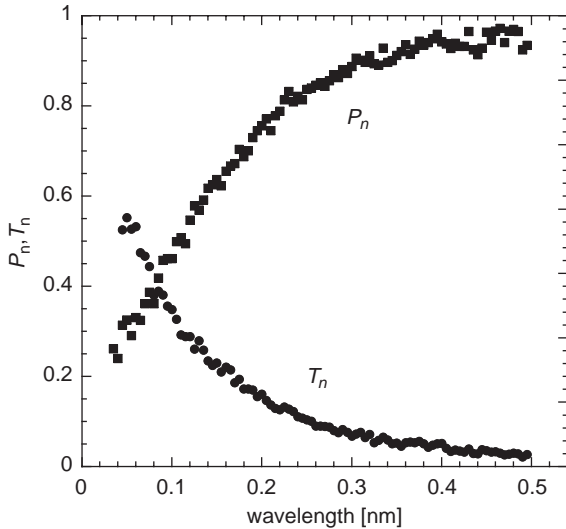

Fig. 4. The neutron polarization P_n (determined from relative transmission measurements using Eq. (2)) and transmission T_n obtained with the compact ^{3}He polarizer on the IPNS SCD beam line.

0.90 and $T_n = 0.072$. A fit of the ratio T_n/T_0 to Eq. (1) yielded $P_{He} = 0.44$. This value is lower than that obtained at NIST due to additional relaxation from magnetic field gradients in the compact solenoid. The discrepancy at large λ is likely due to background including neutrons scattered from our unshielded apparatus.

Our primary goal was to demonstrate the device on the IPNS SCD beam line. As a first step towards future work, we introduced a magnetized sample of single-crystal $Co_{0.92}Fe_{0.08}$, which has a known and nearly perfect analyzing power [17]. The Bragg scattering intensity was measured for two different incident neutron polarization states by rotating the quarterwave plate by $90°$ and optically pumping in the opposite direction. The CoFe sample was magnetized in a vertical 0.2 T field so that the neutron polarization was perpendicular to the momentum transfer Q ($Q = 4\pi/\lambda \sin(\theta)$, where θ is the half scattering angle). We attempted to adiabatically rotate the neutron spins from the solenoid field (along the neutron beam) into the vertical field using a small coil and iron shims. Due to space and time constraints, the rotation occurred over the space of only a few centimeters in a field of a few milli tesla making it difficult to satisfy the adiabatic criteria. We measured an asymmetry of 0.25 in the Bragg scattering intensity out of an expected asymmetry of 0.91. We speculate that the difference is associated with spin transport.

5. Conclusion

We have built a continuously operating ^{3}He spin filter for polarizing a thermal neutron beam at a spallation source. The spin filter is very compact and performed well in a test on the IPNS SCD beam line. A ^{3}He polarization of 44% was continuously maintained, yielding 90% neutron polarization with 7% transmission at a neutron wavelength of 0.3 nm. This test represents the first use of a polarized beam on the SCD. However, non-adiabatic spin transport precluded an accurate test of the analyzing power of a single crystal of $Co_{0.92}Fe_{0.08}$. We intend to improve the ^{3}He polarization in two ways. First, the IPNS SCD instrument is being modified to allow for a modest increase in the size of the solenoid, which should be sufficient to significantly reduce the relaxation due to magnetic field gradients. Second, longer

lifetime cells will be fabricated for the new system. Reduced space constraints and more planning time will allow us to greatly improve the spin transport system. In addition, adiabatic fast passage NMR will allow for much faster flipping of the ^{3}He polarization. Future work at the IPNS SCD should provide important guidance and direction for a ^{3}He polarizer for the SCD at the SNS.

Acknowledgements

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